AFRL-SR-AR-TR-07-0448

REPORT DOCUMENTATION PAGE

NO. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 20-11-2007

2. REPORT TYPE Final Technical

3. DATES COVERED *(From - To)* 04/01/2004-09/30/2007

4. TITLE AND SUBTITLE
Quantum Optical Implementations of Quantum Computing and Quantum Informatics Protocols

5a. CONTRACT NUMBER

5b. GRANT NUMBER FA9550-04-1-0206

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Marlan O. Scully and M. Suhail Zubairy

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)

Institute for Quantum Studies
and Department of Physics
Texas A&M University
College Station, TX 77843-4242

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research (AFOSR)

Dr. Jon Sjogren
AFOSR/NM, Room 713
4015 Wilson Blvd.
Arlington, VA 22203-1954

10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT N/A Distribution Statement A: unlimited

13. SUPPLEMENTARY NOTES N/A

14. ABSTRACT An enumeration of several research efforts funded by the above award is attached. Key aspects reported on include: (a) Sub-wavelength lithography, (b) Subwavelength atom localization, (c) Coherence-induced entanglement and entanglement amplification, (d) Measurement of an arbitrary entangled state, (e) Implementation of optical associative memory, (f) Optically controlled delays for broadband pulses and all-optical beam steering, (g) Measurement of the separation between molecules beyond classical limit, (i) From quantum eraser to Maxwell's demon, (j) Atom microscopy beyond Rayleigh limit, (k) Entanglement criteria, (l) Single-atom laser as a source of entangled light

15. SUBJECT TERMS Quantum computing; quantum informatics; quantum optics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON M. Suhail Zubairy
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)* (979) 862-4047

Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std. Z39.18

Quantum Optical Implementations of Quantum Computing and Quantum Informatics Protocols

AFOSR Grant No.: FA9550-04-1-0206

Final Report

April 1, 2004-September 30, 2007

Principal Investigators:

Marlan O. Scully and M. Suhail Zubairy

Institute for Quantum Studies and
Department of Physics
Texas A&M University
College Station, Texas 77845-4242

I. Technical Status Report

A. Research description

During the report period (April 1, 2004-September 30, 2007) we carried out a number of studies in the field of quantum computing and quantum informatics in accordance with the tasks proposed in the project. In addition we also carried out research that may have an indirect effect on the future of quantum informatics. Following is the summary of our research progress. The details can be found in our enclosed published and submitted papers.

(a) Sub-wavelength lithography:

Optical lithography is widely used in semiconductor device fabrication to write a pattern on a substrate. When exposed to the control light, the photoresist layer coated on the substrate is hardened to form a pattern. After etching, the photoresist layer is removed, leaving the desired pattern printed on the substrate. However, the highest resolution one can achieve with classical uncorrelated light is of half the wavelength. This is due to the fundamental limit of diffraction, the so called Rayleigh criterion.

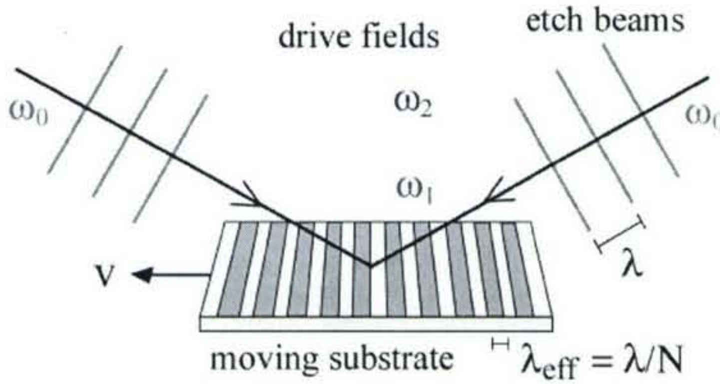

Figure 1: *Scheme for Doppleron lithography using a moving substrate. Two counter-propagating etch beams interfere on a photo-sensitive film. The N-photon Doppleron resonance assisted by two drive fields enables an N-fold reduction in spatial interference resolution.*

The semiconductor industry is always demanding higher resolution. Current wavelength in use has gone into the deep ultraviolet region. Under this situation, many schemes have been proposed to beat the diffraction limit. A potential scheme that generated a great deal of interest is quantum lithography, in which an entangled N-photon state illuminates an N-photon absorbing substrate. Since these photons are correlated, any phase difference along the path will be magnified by a factor of N. Therefore the interference fringes on the substrate become closer to each other and the maximum resolution is now λ/ 2N, which is far below the Rayleigh criterion. In spite of the formal simplicity, this method is not easy to realize due to the following reasons: (a) Preparing and keeping a high order entangled Fock state is quite difficult in experiment; (b) The limited photon number makes the exposure very slow.

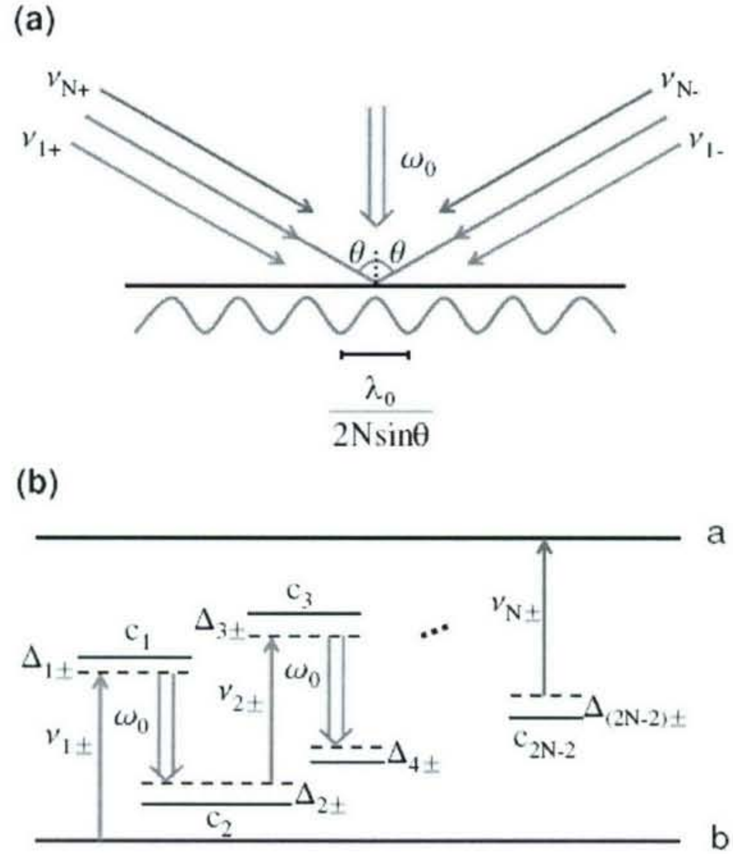

Figure 2: *(a) The scheme of interferometric lithography. Two bunches of signal fields counterpropagate ($\theta = \pi/2$) and the drive field incidents normally. (b) The level structure of the substrate atom. Either bunch of fields together with the drive field satisfies the multiphoton resonance.*

We proposed a novel scheme to overcome these problems to implement quantum lithography using the classical light. This is accomplished by correlating wave vector and frequency in a narrow band multiphoton detection process, so that the subwavelength fringes can be obtained. This method has the advantages of high efficiency, visibility and spatial coherence.

However, a concern is expressed that this scheme can generate only a tight pattern of parallel lines. We showed the procedures to obtain arbitrary patterns in both one and two dimensions. It is done by multiple exposures which correspond to a truncated Fourier series. The modification of resonance condition allows us to choose a fundamental frequency much larger than the signal frequencies, that enables subwavelength resolution. A unique property of our scheme is that there is no frequency upper limit due to the level separation of the substrate. The possibility of large fundamental frequency and many Fourier components make our scheme very suitable to fabricate arbitrary pattern at subwavelength scale.

(b) Subwavelength atom localization

Nano-technology requires an accurate control of the interacting components, both in terms of detection and preparation. This is a major motivation for the considerable attention that was devoted recently to sub-wavelength localization of single particles. High-resolution position measurements of the atom with optical techniques are of particular interest, both from a theoretical, as well as from an experimental, point of view. The interest in the area is largely due to its applications to many areas of optical manipulations of atomic degrees of freedom, such as laser cooling, Bose-Einstein condensation, atom lithography and the measurement of the center of mass wave function of moving atoms. It is well known that optical methods provide better spatial resolution in position measurement of the atom.

We proposed a scheme for sub-wavelength localization of an atom conditioned upon the absorption of a weak probe field at a particular frequency. Manipulating atom-field interaction on a certain transition by applying drive fields on nearby coupled transitions leads to interesting effects in the absorption spectrum of the weak probe field. We exploit this fact and employ a four level system with three driving fields and a weak probe field, where one of the drive fields is a standing wave field of a cavity. We show that the position of an atom along this standing wave is determined when probe field absorption is measured. We find that absorption of the weak probe field at a certain frequency leads to sub-wavelength localization of the atom in either of the two half-wavelength regions of the cavity field by appropriate choice of the system parameters.

We have also proposed a scheme capable of localizing an ensemble of two-level atoms which are bunched together in a volume much smaller than an emission wavelength. Possible realizations include small clusters, few-atom impurities, or atoms trapped, e.g., in optical lattices. The localization relies on the coherent interaction with a standing-wave electromagnetic field. Since the interatomic distances are small, the atoms interact collectively via the environmental vacuum modes. One consequence of this is the appearance of superfluorescence, i.e., the scattered light intensity scales with the number of atoms N squared. We find that the fluorescence light emitted collectively by the ensemble is a function of the ensemble position in the standing wave. In particular, for suitable standing wave parameters and for ensemble positions around the nodes of the standing wave field, the emitted fluorescence intensity sharply drops to a minimum over a narrow spatial region. The narrow width of the dip in the spatial intensity profile is a direct consequence of the collectivity. Since this collective fluorescence intensity profile is our main observable, we discussed the profile in detail in terms of the available free parameters, and show that the profile can be tailored to suit a given localization setup.

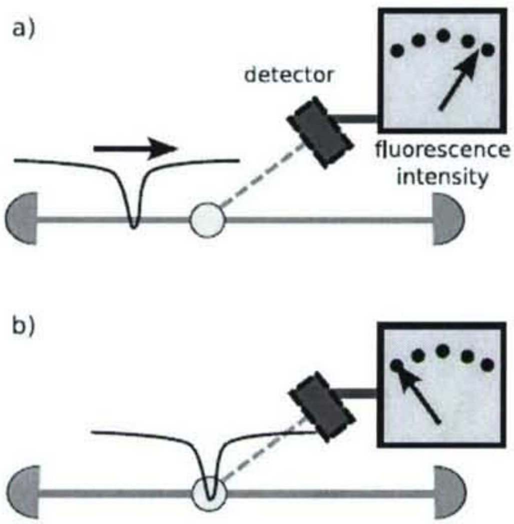

Figure 3: *Scanning-dip scheme. The figure depicts a possible experimental implementation of our scheme. An atom ensemble (green dot) is assumed fixed inside the standing wave field. A detector measures the scattered fluorescence light, while the phase of the standing wave field is varied. The black curve symbolizes the fluorescence intensity profile. If the intensity dip does not coincide with the ensemble position, then a high intensity of fluorescence is detected But if the dip sweeps across the ensemble position, then the measured intensity drops to a minimum over a narrow spatial range, thus providing a sub-wavelength localization.*

Based on these results, we then proposed two schemes which exploit this spatial fluorescence intensity profile to localize an ensemble of atoms.

First, we assumed the sample to be fixed within the standing wave field. In this case, the spatial fluorescence intensity profile can be scanned along the standing wave axis by changing the relative phase of the laser fields forming the standing wave. A continuous measurement of the intensity of the scattered light throughout this scan reveals the position of the sample on a sub-wavelength scale. We further show that this setup also enables one to measure the distance between two samples, the number of atoms in a sample, or the linear dimension of the sample.

Second, we considered an atom cluster flying through the standing wave field. Here a scanning is not possible due to the short interaction time of ensemble and standing wave field. Rather, the absolute intensity of the scattered light can be used to recover the crossing position of the ensemble.

(c) Coherence-induced entanglement and entanglement amplification:

Quantum entanglement lies at the foundation of many areas including quantum computation, quantum communication, and quantum cryptography. Recently, it has been recognized that Gaussian continuous variable entangled states play an important role in quantum information theory. With successful experiments at hand on quantum teleportation with two-mode squeezed states, as well as the experimental realization of entanglement in atomic ensembles, an open question has been the development of a two-mode laser that will generate a macroscopic entangled field.

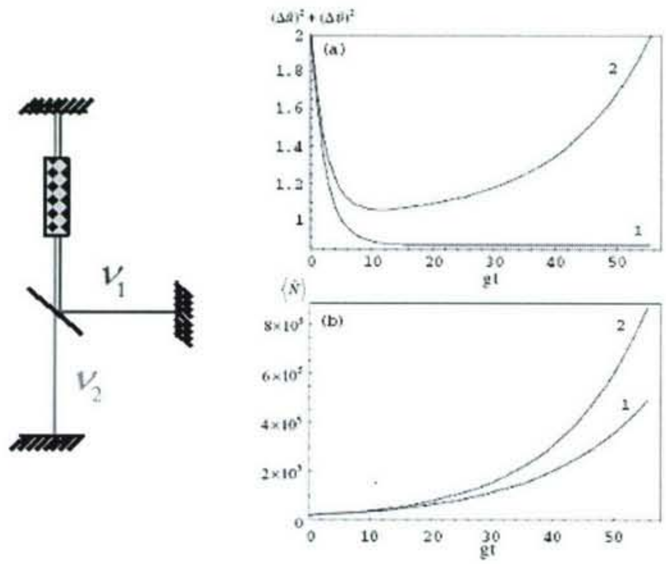

Figure 4: *Schematics of entanglement amplifier using a two-mode correlated emission laser in a doubly resonant cavity. Plotted are the EPR dispersion relation and the average photon number.*

We have shown that atomic coherence is the key to the development of such a laser. In particular, we have developed a detailed theory of a correlated emission laser and have shown that, under certain conditions, such a laser will generate two entangled beams of light potentially containing millions of photons .

Motivated by these considerations, we have also shown atomic coherence can lead to entanglement between two thermal fields at a temperature T. This study relates two important concepts in quantum optics, namely atomic coherence and quantum entanglement, in a natural way. We first show that the passage of a three-level atom in V configuration without coherence can not create entanglement. However, if the excited states are driven by a microwave field, the resulting atomic coherence can lead to entanglement between the thermal fields. We show that, no matter how high the temperature of the fields is, the thermal fields can always be entangled in the presence of atomic coherence.

(d) Measurement of an arbitrary entangled state:

We proposed a scheme for the measurement of a two-mode entangled field-state in a high-Q cavity. The scheme utilizes the momentum distribution spectrum in Raman-Nath regime of a three-level atom in V configuration. Due to the two modes of the electromagnetic field the atom may have x-interactions with mode A, and y-interactions with mode B, causing a complex momentum distribution as compared to a single mode quantized cavity field. The momentum distribution of the atom after interaction with the quantized cavity fields contains the information of the field photon statistics. We can reconstruct the joint photon statistics of the entangled field with the help of the recorded momentum spectrum.

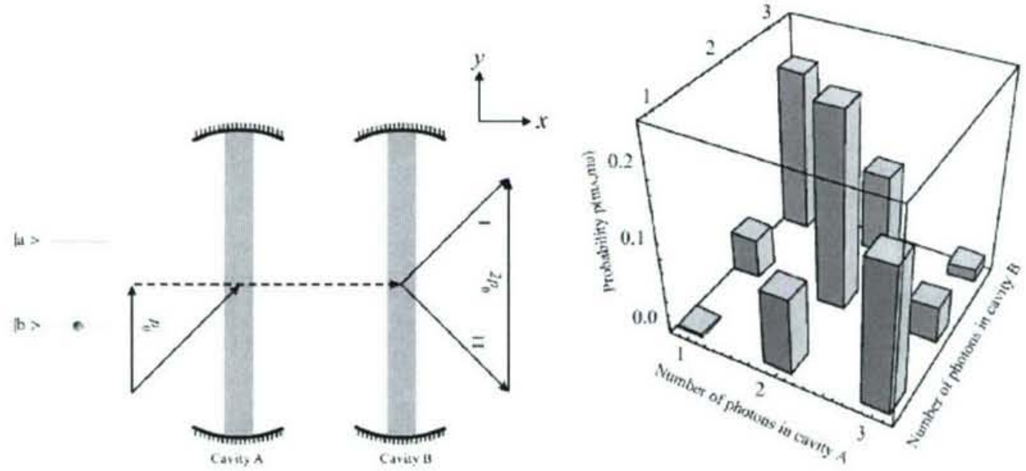

Figure 3: *Left: Schematics of a two-level atom interacting with a standing wave entangled field in two separate cavities. Right: Reconstructed joint photon statistics of the entangled field state in two separate cavities.*

We also proposed to reconstruct the Wigner function of a two-mode entangled field state by injecting two coherent states resonant with each mode into the cavity and then measuring the joint photon statistics of the displaced field.

(e) Implementation of optical associative memory:

Associative memories, which are content-addressable, are required for rapid retrieval of massive data in applications such as identifying human faces and fingerprints. Associative memories are analogous to human brains, which can efficiently handle massive data in an associative and parallel manner. Hopfield proposed a neural network model that presently best describes the main functions of the brain. In this model, linear weighted interconnections are first made between the input neurons (binary memory cells) and "intermediate neurons" (for our convenience, this term is used throughout the letter to refer to the interconnection output), where "intermediate" implies they are non-binary results to be converted into output neurons by the final step of nonlinear thresholding operation. Software implementations of neural networks under conventional computer architectures are serial processing in nature, and will be sluggish in response with growing data sizes. However, optical implementation of Hopfield model has been proved to be highly promising due to the inherent parallelism of optics in establishing multiple interconnections.

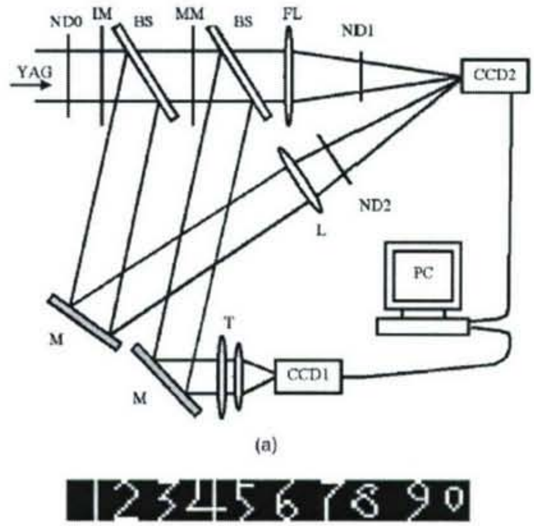

Figure 4: *(a) Schematic of the experimental setup: YAG, collimated Nd:YAG laser, frequency doubled to 532 nm; IM, input mask; BS, beam splitters; MM, memory mask; FL, Fourier-transform lens with focal length 75 cm; ND0–N2, neutral-density filters; M, mirrors; L, convex lens; T, telescope; CCD1, CCD2, cameras; PC, personal computer. (b) Images of numbers from 0 to 9 stored in the memory mask.*

We reported an experimental demonstration of an associative memory model that can be regarded as a modified Hopfield model. The advantage of the modified model is that neuron states, interconnection weights, and thresholds all have non-negative values. Therefore, the intermediate neurons are available through a single step of optical interconnection. In the demonstration, computer-generated holograms (CGHs) were used to optically establish weighted interconnections. The intermediate neuron intensities were detected by a charge-couple device (CCD) camera. A novel and simple real-time thresholding technique was adopted by imaging the threshold intensity simultaneously onto an unoccupied pixel of the same CCD, thus eliminating the separate threshold detector in previous demonstrations. This thresholding scheme also relaxes the requirements on both the dynamic range and linearity of the CCD, because the non-ideal characteristics are identical to the detections of both the intermediate neurons and the threshold. Binarization was completed by a personal computer (PC), which compares the CCD pixel reading of the threshold with those of the intermediate neurons.

(f) Optically controlled delays for broadband pulses and all-optical beam steering:

The recent progress in the study of ultra-short optical pulse generation creates a fundamentally new realm of laser applications in many areas, including material science, information processing, communication and spectroscopy. The fast developing technology of broadband optical pulse shaping requires systems to provide controllable delays for such pulses. For example, an optical buffer can be characterized by the maximum number of bits N that can be simultaneously stored in the buffer. In terms of the bit rate B and the pulse delay τ, the number N is given by $N = B\tau$. The maximum bit rate is however given by $B = 1/T$ where T is the pulse width related to the bandwidth of the system. Thus, N has a simple physical meaning: It is the ratio of the delay time of the buffer and the pulse duration and corresponds to the number of pulses that can be simultaneously processed by the buffer.

We showed that the steep dispersion of an electromagnetically induced transparency (EIT) medium can be used to create large controllable delays for ultra-short pulses by using the system shown in the figure. In particular we showed that it is possible to produce a microsecond delay for 10 picosecond optical pulses, thus yielding a time-delay-bandwidth product of about 10^6. The best product achieved so far in slow-light experiments is 3. An important feature of our scheme is that the delay is continuously controllable by an optical field. The idea is to synthesize dispersion of the system by using the highly steep dispersion of a three-level atomic system with inhomogeneous broadening.

We also proposed a scheme that provides steering of the direction via all optical control. The system is based on steep dispersion of coherently driven medium in which the electromagnetically induced transparency (EIT) occurs.

(g) Measurement of the separation between molecules beyond classical limit:

The measurement of small distances is an important problem with applications to for example nano- and bioscience. For many atomic and molecular systems, this amounts to the search for schemes which allow us to locate one or two atoms or molecules as precisely as possible, frequently with the help of optical methods. Classically, the spatial resolution of optical devices is limited (by diffraction) to about λ, where λ is the optical wavelength. Recently, however, several schemes have been proposed which allow us to localize single atoms with sub-wavelength precision and to beat the classical limit. The general idea here is to encode the position information in observables which do not suffer from the diffraction. Frequently, these studies have focused on single particles, where the position is the only spatial degree of freedom.

We have investigated the spatial properties of a pair of identical atoms or molecules located in a near-resonant standing wave field. Our approach is to monitor the collective resonance fluorescence emitted by the pair. We find three different parameter ranges, depending on the distance of the atoms as compared to the transition wavelength. In the small-distance limit, the dynamics is dominated by the dipole-dipole interaction. For large inter-particle distances, dipole-dipole coupling is negligible, and the main system evolution arises from the interaction with the standing wave field. Finally, in the intermediate region, a rich interplay of the various couplings arises, which however is lifted for strong driving laser fields. The present measurement procedure allows us to distinguish the three cases. In each of the cases, we show how to determine the distance of the two particles and their respective positions relative to the nodes of the standing wave field with fractional-wavelength precision. Our estimates show that the scheme is applicable to inter-particle distances as small as $\lambda / 550$ under realistic conditions.

(h) Detection of bacterial spores through optical backscattering:

Many biological agents such as anthrax spores dispersed in the air would be detrimental to human populations. There is an urgent need for rapid detection and analysis of the suspected airborne chemical and biological agents. Progress in this area has been based on techniques such as fluorescence spectroscopy and UV resonant Raman Spectroscopy. This detection technology requires gathering samples and then transported to a testing facility. The tests detect the incoherent nature of the signal and require long time exposure of the sample which can take quite some time to complete. Technology is needed to do real-time, in-situ and remote testing of air sample for such airborne contaminants.

One of the major components of bacterial spores is the presence of dipicolinic acid (DPA) and its salt calcium dipicolinate in the core of the cell. Calcium dipicolinate (CaDPA) can contribute up to 17% of the dry weight of the spores. Thus, the presence of DPA and CaDPA are a ready-made marker for endospores. This is the key to Raman fingerprinting of the spore.

We have proposed a new approach to detect biological molecules. This method uses an adapted form of Coherent Anti-Stokes Raman Spectroscopy (CARS) that can provide many orders of magnitude enhancement of ordinary CARS signals. Our current scheme is based on enhancing the ground-state molecular coherence. Unfortunately, molecules involving a large number of degrees of freedom will quickly dissipate the molecular coherence among these degrees of freedom. The key point is that we are trying to induce maximal ground-state coherence, as opposed to the usual situation with conventional CARS where the ground-state coherence is not a maximum. With our FAST CARS (femtosecond adaptive spectroscopic techniques applied to CARS) we can prepare the coherence between two vibrational states of a molecule with one set of laser pulses and use higher frequency UV light to probe this coherence at a later time.

We have considered backscattering from a single spore as well as clumps of spores. We showed that the backward signal is sufficiently large to be useful for real-time remote detection and tracing of impurity compounds in the atmosphere using the laser standoff detection technique, by employing maximally prepared quantum coherence through FAST CARS to enhance the backward scattered field from the probed target by many orders of magnitude to a detectable magnitude.

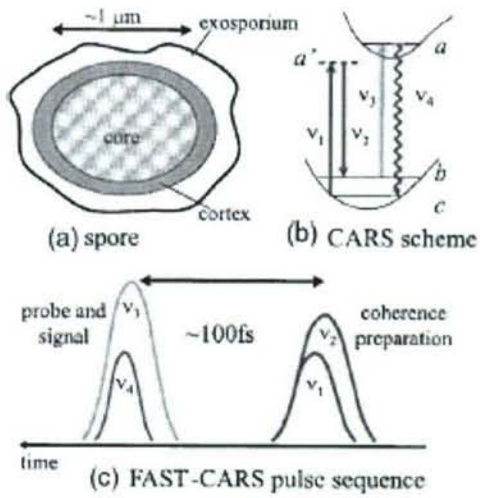

Figure 5: *(a) The structure of a bacterial spore with the core which is approximately spherical and contains about 5 x10^8 dipicolinic acid (DPA) molecules. (b) A simple level scheme used to describe the CARS process in a DPA molecule. (c) The time sequence of a pair of Raman pulses for coherence preparation and a probe pulse scatters off the coherence to produce a signal.*

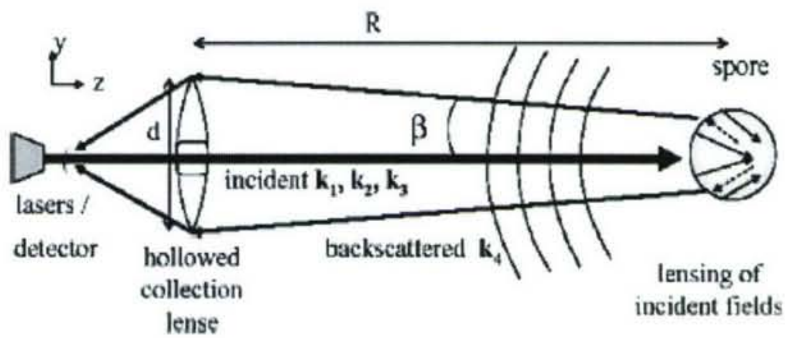

Figure 6: *Typical setup of a femtosecond LIDAR for remote detection of backscattered CARS signal from a distant particle. The size of the spore has been exaggerated*

We estimated the backscattered signal from a cloud of chemical compounds or impurities. In particular, we are interested in standoff detection of atmospheric impurities, such as anthrax spores (see figure). However, this analysis would also be useful for remote sensing in environmental sciences.

(i) From quantum eraser to Maxwell's demon:

The quantum eraser effect of Scully and Druhl dramatically underscores the difference between our classical conceptions of time and features of how quantum processes can unfold in time. Such eyebrow raising features of time in quantum mechanics have been labeled alternately ``the fallacy of delayed choice and quantum eraser", on the one hand, and described ``as one of the most intriguing effects in quantum mechanics", on the other. In the *Science* paper devoted to the Year of Physics, we discuss how the acquisition and erasing of information acquired in the past can effect how we interpret data in the present. The quantum eraser concept has been studied and extended in many different experiments and scenarios. For example: the entanglement quantum eraser, the kaon quantum eraser, and the utilization of quantum eraser entanglement to improve microscopic resolution.

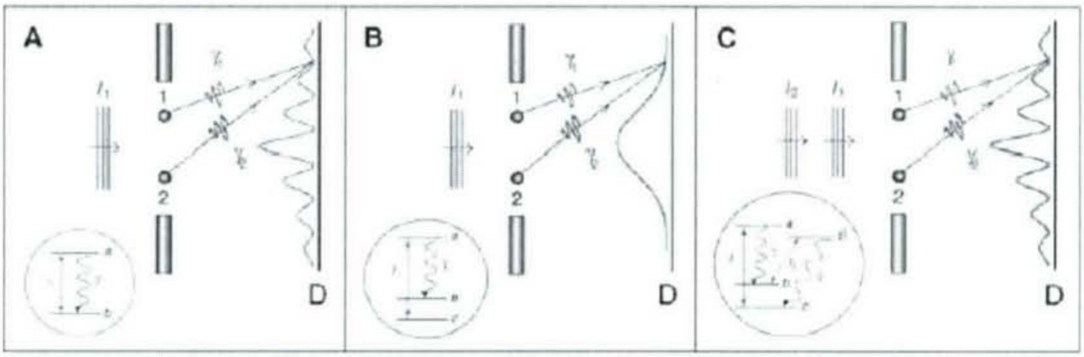

Figure 7: *Three possible configurations and atomic level schemes for two-slit interference developing the quantum eraser idea. Fringes are present in (A), are lost in (B), and are recovered in (C) after erasure of which path information.*

The utilization of an intelligent demon to sort hot from cold atom, and thus run a heat engine from a single thermal bath, was first suggested by Maxwell. Half a century later Szilard introduced and analyzed a single atom heat engine which operated off a single thermal bath by measuring the atom's position. He concluded that the process of measurement was accompanied by entropy production. Fifty years after that Bennett and Landauer clarify the physics by noting that the process of erasing or discarding information is the real source of entropy production. Drawing on ideas from quantum optics, in which lasers and masers operate breaking emission-absorption symmetry, Scully has recently shown that it is possible to devise a different kind of (quantum) heat engine which uses a demonesque thermal sorter to extract work from a single bath. In a series of papers, we analyze several single atom engines which clarify interconnections with and underscore differences between these schemes.

(j) Atom microscopy beyond Rayleigh limit:

Precision measurement of small separations between two atoms or molecules has been of interest since the early days of science. We presented a scheme which yields spatial information on a system of two identical atoms placed in a standing wave laser field. The information is extracted from the collective resonance fluorescence spectrum, relying entirely on far-field imaging techniques. Both the interatomic separation and the positions of the two particles can be measured with fractional-wavelength precision over a wide range of distances from about λ/550 to λ/2.

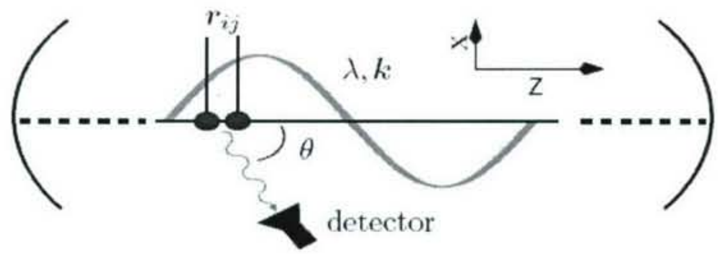

Figure 8: *Two atoms in a standing wave field separated by a distance smaller than half of the wavelength λ of the driving field. The distance of the two atoms is measured via the emitted resonance fluorescence*

(k) Entanglement criteria:

Entanglement has proven to be a valuable resource in quantum information processing. However, determining whether or not a state is entangled is often far from simple. Methods such as the Peres-Horodecki positive partial transpose condition, entanglement witnesses, and hierarchies of entanglement conditions exist, but are not always straightforward to apply. In particular, for systems with continuous degrees of freedom, such as particle position or momentum or the quadrature components of field modes, the number of available criteria for detecting entanglement is very limited. Each of the known criteria detects only a subset of the set of entangled states. In many cases, these criteria are in the form of inequalities. In general they provide only sufficient conditions for detecting entanglement. The utility of most of these inequalities is however limited for non-Gaussian bipartite states. For example, none of these conditions can detect the fact that the state $|0, 1\rangle + |1, 0\rangle$ is an entangled state, though it should be pointed out that it can be shown to be entangled by the application of other entanglement tests. This indicates that there is a need to find additional simple, and ideally, experimentally accessible conditions that can establish whether a state is entangled.

We provided a class of inequalities for detecting entanglement. These inequalities arise from examining uncertainty relations. We examined the observables that are quadratic in the mode creation and annihilation operators. These observables were used previously to define sum and difference squeezing, forms of higher-order squeezing. These quantities and their uncertainties are, in principle, measurable, so that the conditions we derive could be used in a laboratory to detect entanglement. We find that the conditions formulated in terms of these variables lead to a host of other conditions for detecting entanglement. Finally, we also discussed how some of these conditions can be extended to detect entanglement in systems consisting of more than two modes.

We also examined the implications of these conditions [Hillery and Zubairy, Phys. Rev. Lett. 96, 050503 (2006)] for determining when a two-mode state is entangled. We first find examples of non-Gaussian states that satisfy these conditions. We then applied the entanglement conditions to the study of several linear devices, the beam splitter, the parametric amplifier, and the linear phase-insensitive amplifier. For the first two, we find conditions on the input states that guarantee that the output states are entangled. For the linear amplifier, we determined in the limit of high and no gain, when an entangled input leads to an entangled output. Finally, we showed how application of two two-mode entanglement conditions to a three-mode state can serve as a test of genuine three-mode entanglement.

(l) Single-atom laser as a source of entangled light

Traditionally entangled states have been considered between individual qubits. However it has been shown that continuous variable entanglement can offer an advantage in some situations in quantum information science. The classic scheme for the generation of continuous variable entanglement remains the parametric down-conversion. Several experiments have been reported for the generation of entangled states in such systems. There has however been an interest in the generation of entanglement between macroscopic fields generated in optical amplifiers. For example, we have shown recently, based on the study concerning a two-mode correlated spontaneous emission laser (CEL), a CEL can lead to two-mode entanglement even when the average photon number can be very large.

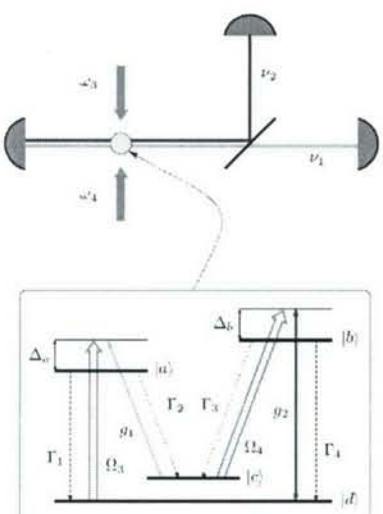

Figure 9: *A single four-level atom is trapped in a doubly resonant cavity and interacts with two cavity modes and two classical laser fields. The inset shows the atomic level scheme.*

A much simpler system relates to a single atom laser and an interesting question relates to the generation of entangled states in such a laser. This is the subject of the present study.

The system we consider is a two-mode version of the single-atom laser that has been experimentally demonstrated by Kimble's group at CALTECH. We show that, under certain realizable conditions, a two-mode single-atom laser, can serve as a source of macroscopic entangled light source.

An important question in the generation of continuous variable entanglement in quantum optical systems is the way such entanglement can be measured experimentally. This is a hotly discussed subject in recent years. Several inequalities involving the correlation of the field operators have been derived that are based on the separability condition of the field modes. A violation of these inequalities provides an evidence of entanglement. These inequalities can, in general, provide only the sufficiency condition for entanglement and only, in some very specific instances, lead to sufficient and necessary conditions for entanglement. We used the inequality based on quadrature measurement of the field variables for the test of entanglement.

B. Papers published/submitted

During the report period, the following papers were published / submitted:

1. "Cavity QED based quantum walk", T. Di, M. Hillery, and M. S. Zubairy, Phys. Rev. A **70**, 032304 (2004).

2. "Measurement of entangled state via atomic beam deflection in Bragg's regime", A. H. Khosa, M. Ikram, and M. S. Zubairy, Phys. Rev. A **70**, 052312 (2004).

3. ``Quantum shell game: finding the hidden pea in a single attempt", A. Muthukrishnan, M. Jones, M. O. Scully, and M. S. Zubairy, J. Mod. Opt. **16**, 2351 (2004).

4. "Generation of arbitrary two-qubit entangled states in cavity QED", T. Di and M. S. Zubairy, J. Mod. Opt. **16**, 2387 (2004).

5. "Cavity QED: Applications to Quantum Computing", H. Xiong and M. S. Zubairy, in *Quantum Communications and Quantum Imaging II (Vol. 5551),* edited by R. E. Mayer and Y.-H. Shih (SPIE Press 2004), pp 94-104.

6. ``Correlated spontaneous emission laser as an entanglement amplifier", H. Xiong, M. O. Scully, and M. S. Zubairy, Phys. Rev. Lett. **94**, 023902 (2005).

7. ``Time and the quantum: Erasing the past and impacting the future", Y. Aharonov and M. S. Zubairy, Science **307**, 875 (2005).

8. "Quantum teleportation of an arbitrary superposition of atomic Dicke states", T. Di, A. Muthukrishnan, M. O. Scully, and M. S. Zubairy, Phys. Rev. A **71**, 062308 (2005).

9. ``Coherence induced entanglement", F. Li, H. Xiong, and M. S. Zubairy, Phys. Rev. A **72**, 010303 (Rapid Communications) (2005).

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30. "Preservation of nonclassicality in the continuous-variable quantum teleportation", T. Di, F. Li, and M. S. Zubairy, Opt. Commun. **260**, 633 (2006).

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44. "Factoring numbers with waves", M. S. Zubairy, Science **316**, 554 (2007).

45. "Atom localization and wave function determination via multiple simultaneous quadrature measurements", J. Evers, S. Qamar, and M. S. Zubairy, Phys. Rev. A **75**, 053809 (2007).

46. "The role of quantum noise on nonclassical two-photon correlation in an extended medium". C. H. R. Ooi and M. S. Zubairy, Phys. Rev. A **75**, 053822 (2007).

47. "Generating entangled states of continuous variables via cross-Kerr nonlinearity", Z.-M. Zhang, A. H. Khosa, M. Ikram, and M. S. Zubairy, J. Phys. B: At. Mol. Opt. Phys. **40**, 1917 (2007).
48. "Influence of pump phase fluctuations on entanglement generation using correlated emission laser", S. Qamar, H. Xiong, and M. S. Zubairy, Phys. Rev. A **75**, 062305 (2007).

49. "Disentanglement in a two-qubit system subject to dissipation environments", M. Ikram, F.-L. Li, and M. S. Zubairy, Phys. Rev. A **75**, 062336 (2007).

50. "Quantum lithography with classical light: Generation of arbitrary patterns", Q. Sun, P. R. Hemmer, and M. S. Zubairy, Phys. Rev. A **75**, 065803 (2007).

51. "Entanglement generation in a two-mode quantum beat laser", M. Ikram, G.-X. Li, and M. S. Zubairy, Phys. Rev. A **76**, 042317 (2007).

52. "Manipulation of the Raman process via incoherent pump, tunable intensity, and phase control", L.-G. Wang, S. Qamar, S.-Y. Zhu, M. S. Zubairy, Phys. Rev. A (submitted).

53. "Resonant interferometric lithography beyond the diffraction limit", M. Kiffner, J. Evers, and M. S. Zubairy, Phys. Rev. Lett. (submitted).

54. "Entanglement in a parametric converter", S.-Y. Lee, S. Qamar, H.-W. Lee, and M. S. Zubairy, J. Phys. B: At. Mol. Opt. Phys. (submitted).

55. "Semiclassical and quantum theory of a single atom laser", O. Cizmeci, J. Bergou, and M. S. Zubairy, Phys. Rev. A (submitted).

C. List of professional personnel involved

The following personnel participated in the research effort:

1. Marlan O. Scully, Distinguished Professor
2. M. Suhail Zubairy, Professor
3. Ashok Muthukrishnan, Post-Doctoral Fellow
4. Fuli Li, Visiting Scientist
5. Yaping Yang, Visiting Scientist
6. Han Xiong, Graduate student

7. Tiegang Di, Graduate student

8. Juntao Chang, Graduate student

9. Qingqing Sun, Graduate student

D. Papers presented at meetings, conferences, seminars

The results were presented at several conferences and lecture series. These include:

1. M. S. Zubairy, ``From correlated emission laser to an entanglement amplifier", at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, April 15, 2004.

2. M. O. Scully, "Using Quantum Mechanics to Detect Anthrax (and much more)" NSF REU program, Chemistry Department TAMU, June 25, 2004.

3. M. O. Scully, Final Keynote Address, Fields Institute Conference on Quantum Information and Quantum Control, University of Toronto, Toronto, Canada, July 23, 2004

4. M. O. Scully, "Quantum Controversy: From Maxwell's Demon and Quantum Eraser to Black Hole Radiation" Frontiers of Quantum and Mesoscopic Thermodynamics Conference, Prague, Czech Republic, July 26, 2004.

5. M. S. Zubairy, ``Cavity QED-based quantum computing", SPIE Conference on Quantum Communications and Quantum Imaging II, held at Dever, Colorado (August 4-6, 2004)

6. M. S. Zubairy, ``Correlated emission laser as an entanglement amplifier", Feynman Festival, University of Maryland, Baltimore (August 20-26, 2004).

7. M. S. Zubairy, "Master equation approach to Bose-Einstein condensation" (Invited lecture) at the Princeton BEC Symposium, Princeton University, Oct. 14-15, 2005.

8. M. S. Zubairy, ``Quantum teleportation via conditional measurements", at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, Nov. 18, 2004.

9. M. O. Scully, "Fundamental and Applied Quantum Eraser" New Frontiers in Quantum Theory and Measurement Conference, Schloss Reisensburg, Germany 09/04/04

10. M. S. Zubairy, A series of three invited lectures at the International Workshop on Quantum Informatics, Hong Kong, December 16 – 18, 2004.

11. M. S. Zubairy, A series of 5 lectures on Quantum Computing at the COMSATS Institute for Information Technology, Islamabad, Pakistan, December 26, 2004-January 5, 2005.

12. M. S. Zubairy, ``Time and the quantum: Erasing the past and impacting the future", Colloquium at the COMSATS Institute for Information Technology, Islamabad, Pakistan, January 6, 2005.

13. M. S. Zubairy, ``Quantum entanglement and quantum computing", Colloquium at the Pakistan Institute for Engineering and Applied Sciences, Islamabad, Pakistan, January 4, 2005.)

14. M. O. Scully, "The EPR Paradox Revisted", AMO Physics Seminar, TAMU Jan. 18, 2005.

15. M. S. Zubairy, ``Quantum computing: Cavity QED based schemes", (Invited paper) at the SPIE Conference on Advanced Optical and Quantum Memories and Computing II, San Jose, January 25-26, 2005.

16. M. S. Zubairy, ``From subluminal to superluminal; light propagation via phase control", (Invited paper) at the SPIE Conference on Advanced Optical and Quantum Memories and Computing II, San Jose, January 25-26, 2005.)

17. M. O. Scully, "Locality vs. Nonlocality in quantum mechanics or (How to make quantum mechanics look like hidden variable theory and vice versa)", AMO Physics Seminar, TAMU, Feb. 1, 2005.

18. M. O. Scully, "The role of observation and the observer in the quantum micro cosmos", SMU, Feb, 7, 2005.

19. M. O. Scully, "Information Erasure from Maxwell's Demon to Wigner's Friend", AMO Physics Colloquium, UNT, Feb. 24, 2005.

20. M. S. Zubairy, ``From correlated emission laser to entanglement amplifier", (Invited talk) at the JSPS-PRISM-TAMU Symposium on Quantum Material Science, Princeton University, February 21-22, 2005.)

21. M. O. Scully, "From EPR to quantum eraser: The Role of Observation and the Observer in the Quantum Micro Cosmos," TASPS, TAMU, March 4, 2005.

22. M. O. Scully, "Do EPR-Bell Correlations Require a Non-Local Interpretation of Quantum Mechanics?" AMO Physics Seminar, TAMU, March 8, 2005.

23. M. S. Zubairy, ``Quantum entanglement: Microscopic and macroscopic", Seminar at the Department of Physics, Louisiana State University, Baton Rouge, March 18, 2005.

24. M. S. Zubairy, ``Quantum eraser", Seminar at the Department of Physics, Texas A&M University, March 23, 2005.

25. M. S. Zubairy, ``Coherence induced entanglement", at the Quantum Computing Seminar Series, Department of Computer Sciences, Texas A&M University, March 23, 2005.

26. M. O. Scully, "From Bose and Einstein to Bogoliubov and beyond: Aa rich tradition of optical and statistical physics," International Conference on Theoretical Physics, Moscow Russia, April 11-16, 2005

27. M. O. Scully, "Micromaser applications--From quantum eraser to quantum thermodynamics and Unruh radiation", Frontiers of Quantum Optics and Applications Symposium, April 16-21, 2005.

28. M. O. Scully, "Quantum eraser - Impacting the future by erasing the past" University of New Mexico, Center for Advanced Studies 2005 CAS Distinguished Lecture I, April 26, 2005.

29. M. O. Scully, "Frozen light - the tip of the iceberg" , University of New Mexico, Center for Advanced Studies 2005 CAS Distinguished Lecture II, April 27, 2005.

30. M. O. Scully, A New Approach to Quantum Chemistry Based on Dimensional Scaling, University of New Mexico, Center for Advanced Studies 2005 CAS Distinguished Lecture III, April 28, 2005.

31. M. S. Zubairy, ``Quantum entanglement: Microscopic and macroscopic", Colloquium at the Department of Physics, University of Arkansas, Fayyettville, April 29, 2005.

32. M. O. Scully, "From Bose and Einstein to Bogoliubov and Beyond: a rich tradition of optical and statistical physics," 93rd Statistical Mechanics Meeting, Rutgers, The State University, May 15, 2005.

33. M. S. Zubairy, ``An entanglement amplifier", (Invited paper) at the Conference on Fluctuations and Noise in Photonics and Quantum Optics III, in Austin, Texas, (May 24-26, 2005).)

34. M. O. Scully, 'Quantum eraser effects: Past, present and future," SPIE Fluctuation and Noise Confeernce, Austin, Texas, May 23-26, 2005.

35. M. O. Scully, "Quantum Controversy and the Bose Condensate," Quantum Theory: Reconsideration of Foundations 3 Conference, June 6-11, 2005.

36. M. O. Scully, "Quantum Eraser: from Wigner's Friend to Maxwell's Demon" Quantum Theory: Reconsideration of Foundations 3 Conference, June 6-11, 2005.

37. M. S. Zubairy, ``Quantum computing", Invited lecture series at the Nathiagali Summer College at Nathiagali, Pakistan, (June 27-July 1, 2005).

38. M. S. Zubairy, ``Coherence induced entanglement", (Invited paper) at the SPIE Conference on Quantum Communications and Quantum Imaging III, held in San Diego (July 31-August 4, 2005).

39. M. S. Zubairy, ``Quantum entanglement: Microscopic and macroscopic", (Invited paper) at the KIAS-KAIST 2005 Workshop on Quantum Information Science, held in Seoul, Korea (August 22-24, 2005).

40. M. S. Zubairy, ``Propagation of Broadband Pulse in EIT Medium", at the Annual Meeting of the Optical Society of America, Tucson, Arizona, Oct. 17-20, 2005.

41. M. S. Zubairy, "Quantum Entanglment: Measurement Criteria and Applications" (Invited talk) at the Symposium on Mathematics of Quantum Computation and Quantum Technology, Texas A&M University, November 13 - 16, 2005.

42. M. S. Zubairy, "Quantum computing: New frontiers", (Keynote speaker) at Saudi Physical Society Meetoing, Mecca, Saudi Arabia, Nov. 27-29, 2005.

43. M. S. Zubairy, "Quantum Entanglement: Microscopic and macroscopic", (Special lecture) at the King Khalid University, Abha, Saudi Arabia (Nov. 27, 2005).

44. M. S. Zubairy, "Atomic coherence and applications", (Invited series of lectures) at The 13th APCTP-KIAS Workshop on Nanoscale and Mesoscopic Systems: Mesoscopics meets Quantum Optics, at the Pohang University of Science and Technology, Korea, Dec. 12-13 (2005).

45. M. S. Zubairy, "Correlated Emission Laser as an Entanglement Amplifier", (Invited speaker) at the International Conference on Quantum Optics, Chinese University of Hong Kong, Hong Kong, China, Dec. 17-20 (2005).

46. M. S. Zubairy, "Quantum entanglement: microscopic and macroscopic", (special lecture) at COMSATS Institute of Information Technology, Islamabad, Dec. 27, (2005).

47. M. S. Zubairy, "Coherent atomic interactions", (special lecture) at COMSATS Institute of Information Technology, Islamabad, Dec. 29, 2005.

48. M. S. Zubairy, "All optical controlled steering of light" (Invited lecture) at the Conference on Advanced Optical and Quantum Memories and Computing III, in San Jose, California, Jan. 24-25 (2006).

49. M. S. Zubairy, "Time and quantum: Quantum eraser" (Invited lecture) at the Wheelerfest, Princeton University, February 24-25 (2006).

50. M. S. Zubairy, "Quantum interferometry: From quantum eraser to quantum microscopy and lithography", (Invited lecture) at TAMU-Princeton Joint Seminar, May 19-20 (2006).

51. M. S. Zubairy, "Quantum Computing", Invited Lecture Series at the *International Workshop on Quantum Informatics and Quantum Devices*, Nathiagali, Pakistan, June 26 – July 01 (2006).

52. M. S. Zubairy, "Quantum lithography and microscopy", (Invited lecture) at the *International Conference on Cohenent Control of the Fundamental Processes in Optics and X-ray Optics*, Nizhny Novgorod, Russia, June 29-July 3 (2006).

53. M. S. Zubairy, "Quantum interferometry: From Quantum Eraser to Quantum Lithography", (Theoretical Physics Colloquium), at the University of Ulm, Ulm, Germany, July 27 (2006).

54. M. S. Zubairy, "Quantum interferometry: From Quantum Eraser to Quantum Lithography", (Colloquium) at the Max-Planck Institute for Nuclear Physicvs, Heidelberg, Germany, August 31 (2006).

55. M. S. Zubairy, "Quantum lithography with classical light", (Invited talk) at the Third Feynman Festival, University of Maryland, August 25-29 (2006).

56. M. S. Zubairy, "From quantum eraser to quantum lithography", (Invited talk) at the *2nd Asia-Pacific Conference and KIAS-KAIST 2006 Workshop on Quantum Information Science,* KIAS International Conference Hall, Seoul, Korea, August 27- 30 (2006).

57. M. S. Zubairy, "Quantum interferometry: From Quantum Eraser to Quantum Lithography", (Seminar) at the Northwestern University, Evanston, September 28 (2006).

58. M. S. Zubairy, "Atomic microscopy and quantum lithography", (Invited lecture) at the Atom Optics Meeting , Schloss Reisenburg, Germany, October 16-17 (2006).

59. M. S. Zubairy, "Quantum interferometry: From quantum eraser to quantum lithography", Joint Complex Quantum Systems/Nonlinear Dynamics Seminar, University of Texas, Austin, October 28 (2006).

60. M. S. Zubairy, "Atomic coherence and applications", (Lecture series), Korean Institute for Advanced Studies, Seoul, Korea, December 26-29 (2006).

61. M. S. Zubairy, "Coherent atomic effects and applications", (Lecture series), International Symposium on Quantum Optics, at the Center for Quantum Physics, CIIT, Islamabad, Jan. 8-10 (2007).

62. M. S. Zubairy, "From Albert Einstein to John Bell and beyond", (Special seminar), Texas A&M University at Qatar, Doha, Qatar, February15 (2007).

63. M. S. Zubairy, "Quantum computing: New frontiers", (Invited speaker), International Symposium on Contemporary Physics, Islamabad, Pakistan, March 26 - 30, (2007).

64. M. S. Zubairy, "Quantum lithography and microscopy", (Invited speaker), Princeton-TAMU Symposium on Quantum Mechanics, Informatics, and Control, Princeton University (April 6-7, 2007).

65. M. S. Zubairy, "Spectroscopic methods for quantum lithography and microscopy", (Invited speaker), International Symposium on the Recent Progress in Optical Spectroscopy and its Applications, Hong Kong (May 7-9, 2007).

66. M. S. Zubairy, "Quantum entanglement: Measures and Applications", (Invited speaker), SPIE Conference on Noise and Fluctuations in Photonics, Quantum Optics, and Communications, Florence, Italy (May 21-23, 2007).

67. M. S. Zubairy, "Quantum interferometry: From quantum lithography to sub-wavelength microscopy", (Invited speaker), International Conference on Quantum Information (ICQI), Rochester, New York (June 10-15, 2007).

68. M. S. Zubairy, "EIT, slow and fast light, and applications" (Seminar), University of Ulm, Germany, (July 19, 2007).

E. Patents:

1. M. S. Zubairy (with G. Chen and Z. Diao), A Quantum Circuit Design for Grover's Algorithm, US Patent No. 10/271652

F. Honors/Awards

1. M. O. Scully, Arthur L. Schawlow Prize of the American Physical Society.

2. M. S. Zubairy, Humboldt Research Prize by the Alexander von Humboldt Foundation.